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## High Energy Gamma–Radiation from the Galactic Center due to Neutralino Annihilation

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### Abstract

We study the NGS (Non-dissipative Gravitational Singularity) model, which successfully describes the non-linear stage of evolution of perturbations (see [1], [2] and references therein). This model predicts DM density distribution  $\rho(r) \sim r^{-\alpha}$  with  $\alpha \simeq 1.8$  which holds from very small distances  $r_{\min} \simeq 0.01$  pc up to very large distances  $r_{\max} \simeq 5$  Mpc. Assuming the neutralino to be a CDM particle, we calculate the annihilation of neutralinos in the vicinity of the singularity (Galactic Center). If neutralinos are the dominant component of DM in our Galaxy, the produced energy is enough to provide the whole observed activity of the GC. Neutralinos of the most general composition and of mass in the range  $20 \text{ GeV} \leq m_\chi \leq 1 \text{ TeV}$  are considered. We find the neutralino compositions which give the relic density needed for the Mixed Dark Matter (MDM) model and we evaluate for these compositions the high-energy ( $E_\gamma > 100$  MeV) gamma-ray flux under the constraint that the radio flux is lower than the observational limit. The compositions with the detectable gamma-ray flux which we found are provided by a set of almost pure gaugino states with the neutralino mass between 100 and 500 GeV.

We demonstrate that a detectable high-energy gamma-ray flux is produced by the neutralino annihilation also in the case when neutralinos provide a small fraction (down to 0.1%) of the DM in our Galaxy. The predicted flux is  $F_\gamma \sim 10^{-7} - 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$  for  $E_\gamma \gtrsim 300$  MeV

## 1. Introduction.

The spectrum of perturbations as observed by COBE, IRAS and CfA is most naturally explained by the Mixed Dark Matter (MDM) model [3] with  $\sim 60 - 70\%$  of Cold Dark Matter (CDM),  $\sim 20 - 30\%$  of Hot Dark Matter (HDM) and  $\sim 10\%$  of baryonic matter. The most plausible candidates for the MDM particles are the  $\tau$ -neutrino as a HDM particle and the neutralino  $\chi$  as a CDM particle. According to this model  $\delta\rho/\rho$  on the galactic scale  $\lambda \sim 1$  Mpc is dominated by the CDM particles, while on the scales  $\lambda \sim 10 - 100$  Mpc  $\delta\rho/\rho$  is dominated by the HDM particles. The baryons, which decoupled from the radiation much later than CDM particles, streamed into the potential wells built by the space distribution of CDM particles. As a rough estimate of the average fraction of the baryon density in the halo one can take the relative density of baryons in the whole Universe ( $\sim 10\%$ ) and this assumption does not contradict the recent observations of MACHO candidates[4].

When  $\delta\rho/\rho$  on the galactic scale approaches one, the evolution of fluctuations enters the non-linear stage. There are two solutions for this stage, determined by the space symmetry of the initial fluctuations, i.e. of those with  $\delta\rho/\rho \sim 1$ . The first solution was found by Zeldovich [5] for a case of asymmetric initial distribution of matter relative to the local maximum of density. In this case the evolution terminates with the production of the flat formations – the Zeldovich pancakes. For this solution the potential well within a galaxy is not formed and the CDM gas is not self-trapped.

The other solution, found first in ref. [1], exists if the initial distribution is more symmetric. In this case a strong singularity is formed and the CDM gas is self-trapped. Each singularity, which is called Non-dissipative Gravitational Singularity (NGS), is associated with a galaxy. The main predictions of this model according to ref. [2], can be summarized as follows:

i) The density distribution of CDM particles centered at a NGS is given by

$$\rho(r) \propto r^{-\alpha} \quad (1)$$

with  $\alpha \simeq 1.8$ . The distribution (1) is valid down to very small distances  $r_{\min}$  where a cut off can be caused by several phenomena[2]. The largest value of  $r_{\min}$  is related to the case of a black hole in the NGS. For a black hole with a mass  $M \sim 10^6 M_\odot$  this value is  $r_{\min} \sim 0.01$  pc. The maximum value up to which the distribution (1) holds is not predicted by the NGS model, because this is the initial condition for the non-linear problem. We suggest that the value of  $r_{\max} \sim 5$  Mpc, as it is given by the two-point correlation function, is determined by the scale where HDM dominates in

the perturbation amplitudes. The distribution (1) is in excellent agreement with the observations.

ii) The predicted density of CDM at the distance  $r_\odot = 8.5$  kpc from the Galactic Center is equal to  $\rho_{\text{CDM}}^{\text{loc}} \simeq 0.2$  GeV, if we take  $\langle \rho_{\text{CDM}} \rangle \approx 0.7 \rho_c$  ( $\rho_c = 1.88 \cdot 10^{-29} h^2 \text{ g cm}^{-3}$ ). This result is in a good agreement with the DM density obtained from the rotational curves in our Galaxy,  $0.3 \text{ GeV cm}^{-3} \leq \rho_{\text{DM}}^{\text{loc}} \leq 0.43 \text{ GeV cm}^{-3}$ , for the total DM density.

iii) Annihilation of CDM particles in the vicinity of the singularity results in a pointlike radiation source in the Galactic Center.

In ref.[2] the luminosity due to the neutralino annihilation in the NGS model has been evaluated, together with the ensuing gamma-ray and radio fluxes. Comparisons of the calculated fluxes with the available experimental upper limits were then used in ref.[2] to obtain lower limits for neutralino masses in the case of almost pure neutralino configurations (either gauginos or higgsinos) and under the hypothesis that neutralinos provide a fraction of about 70% of DM density in the Galactic halo. In ref.[2] the theoretical evaluations referred mainly to not too heavy neutralinos, i.e.  $m_\chi \leq O(m_W)$ .

In this paper we present a more general analysis valid for a wide range of neutralino masses ( $20 \text{ GeV} \leq m_\chi \leq 1 \text{ TeV}$ ) and of neutralino compositions and we mainly address the question: can the annihilation of neutralinos around the singularity result in detectable gamma-ray flux at energy  $E_\gamma \gtrsim 100 \text{ MeV}$ ? Apart from the favourite case when the neutralino is the only CDM particle, we shall study the case of arbitrary  $\Omega_\chi = \rho_\chi / \rho_c$ , which in the framework of the MDM model implies the presence of other CDM particles X with  $\Omega_X > \Omega_\chi$

## 2. Neutralino

We shall consider the neutralino in the context of the Minimal Supersymmetric Standard Model (MSSM). The neutralino is defined as the lowest-mass linear combination

$$\chi = Z_{11}\tilde{W}_3 + Z_{12}\tilde{B} + Z_{13}\tilde{H}_u + Z_{14}\tilde{H}_d \quad (2)$$

where  $\tilde{W}_3$  and  $\tilde{B}$  are the SU(2) and U(1) neutral gauginos and  $\tilde{H}_{u,d}$  are the higgsinos. The space of neutralino states is determined by three independent parameters: the masses of  $\tilde{B}$  and  $\tilde{W}_3$ ,  $M_1$  and  $M_2$ , respectively, with the GUT relation between them  $M_1 \simeq 0.5 M_2$ , the Higgs mixing parameter  $\mu$ , and the ratio of the two v.e.v.'s which give masses to up-type and down-type quarks,  $\tan \beta = v_u/v_d$ . The natural range for  $\tan \beta$  is:  $1 \leq \tan \beta \leq m_t/m_b$ .

In the calculations discussed below the parameters  $M_2$  and  $\mu$  are varied in the wide ranges:  $0 < M_2 < 6$  TeV and  $-3$  TeV  $< \mu < 3$  TeV.

The neutralino is assumed to be the lightest SuSy particle and to be stable because of R-parity conservation. The decoupling of neutralinos in the early Universe with the subsequent annihilation results in the neutralino relic abundance

$$\Omega_\chi h^2 = 2.13 \cdot 10^{-11} \left( \frac{T_\chi}{T_\gamma} \right)^3 \left( \frac{T_\gamma}{2.7^\circ K} \right)^3 N_f^{1/2} \left( \frac{GeV^{-2}}{ax_f + \frac{1}{2}bx_f^2} \right), \quad (3)$$

where  $h$  is the dimensionless Hubble parameter,  $x_f = T_f/m_\chi$ ,  $T_f$  is the neutralino freeze-out temperature,  $T_\gamma$  and  $T_\chi$  are the present temperatures for relic photons and neutralinos,  $N_f$  denotes the effective number of degrees of freedom at the freeze-out temperature.  $N_f \sim 100$  for  $m_\chi \geq m_W$ . The thermal average of the  $\chi\chi$ -annihilation cross-section  $\langle \sigma v \rangle$  at the temperature  $T = xm_\chi$  is parameterized in (3) as

$$\langle \sigma v \rangle = a + bx \quad . \quad (4)$$

The expression  $ax_f + 1/2 bx_f^2 \equiv \langle \sigma v \rangle_{int}$  in eq.(3) represents the integrated cross section from  $T_f$  to the present temperature.

Since we wish to discuss neutralinos with masses up to 1 TeV, many channels have to be considered in the neutralino annihilation processes. In the present paper, for the values of  $\langle \sigma v \rangle$  and of the neutralino relic abundance, we employ the results of the thorough analysis of ref.[6], where the full set of possible final states have been considered: fermion-antifermion pair, pair of two (neutral and charged) Higgses, one Higgs boson-one gauge boson states and pair of two gauge bosons. In the evaluation of  $\sigma$ , the exchanges of the following particles :  $Z$  boson, Higgses, sfermions  $\tilde{f}$ , neutralinos and charginos, have been included depending on the specific final state. As for the values of the masses of the neutral Higgs bosons, the two CP-even:  $h$ ,  $H$  (of masses  $m_h$  and  $m_H$ , with  $m_h < m_H$ ) and the CP-odd:  $A$  (of mass  $m_A$ ), we employed the usual relationships which include radiative corrections. These imply that if, for instance,  $m_h$  is used as a free parameter, then  $m_A$  and  $m_H$  turn out to be dependent on  $m_h$ ,  $\tan\beta$  and also (through the radiative terms) on  $m_t$  (top-quark mass) and  $\tilde{m}$  (mass of the top scalar partners, considered here as degenerate). We remind that the LEP lower limit for  $m_h$  is  $m_h > 50$  GeV [7].

In our further calculations we give most attention to those compositions of  $\chi$  which provide  $\Omega_\chi \simeq 0.6 - 0.7$ . However, we shall also consider a case of smaller  $\Omega_\chi$ , which implies that neutralino compose only a fraction of CDM in the Universe.

### 3. The pointlike source in the Galactic Center due to $\chi\chi$ -annihilation

For the distribution (1) annihilation between neutralino pairs would be very efficient in a region of linear size  $\simeq r_{min} \simeq 0.01$  pc which implies for the source the angular size  $\simeq 10^{-6} - 10^{-7}$  rad. The total luminosity of the source is

$$L = 2m_\chi \langle \sigma v \rangle_0 P \quad (5)$$

where  $P$  is

$$\begin{aligned} P &\equiv \frac{1}{m_\chi^2} \int dr 4\pi r^2 \rho_\chi^2(r) \\ &= \frac{2\pi}{0.3} \frac{1}{m_\chi^2} (\rho_\chi^{\text{loc}})^2 r_\odot^3 \left( \frac{r_{min}}{r_\odot} \right)^{-0.6} \end{aligned} \quad (6)$$

and  $\langle \sigma v \rangle_0$  denotes the value of  $\langle \sigma v \rangle$  at the present temperature.

Here we have employed for the neutralino density profile in our Galaxy the NGS distribution of Eq.(1) and have denoted by  $\rho_\chi^{\text{loc}}$  the local (solar neighborhood) neutralino density. Due to different space distribution of CDM and HDM in the Universe, we expect  $\rho_\chi^{\text{loc}}/\rho_{\text{DM}}^{\text{loc}} \gtrsim \Omega_\chi/\Omega$ . However, for simplicity we used in our calculations  $\rho_\chi^{\text{loc}}/\rho_{\text{DM}}^{\text{loc}} = \Omega_\chi/\Omega$ . For  $r_{min}$  we shall use the capture radius of the black hole with mass  $M \sim 10^6 M_\odot$  [2]:  $r_{min} \simeq 0.01$  pc.

In the evaluation of cross section  $\langle \sigma v \rangle_0$  in Eq.(5) we use the approximation  $\langle \sigma v \rangle_0 \simeq a$ , since at present, inside the Galaxy, neutralinos most probably have a gaussian velocity distribution with an average value  $\bar{v} \simeq 300$  km s $^{-1}$  and consequently  $x \simeq \bar{v}^2/6 \sim 10^{-7}$ . Annihilation of neutralinos into quarks and leptons thorough the main channels  $b\bar{b}$ ,  $t\bar{t}$ ,  $W^+W^-$ , and  $ZZ$  has been taken into account. The part of luminosity due to fermion production is dominated by heavy (b and t) quarks. The  $b(\bar{b})$  quarks, either produced directly or by  $t(\bar{t})$  decays, do not decay within the confinement region, but produce copiously lighter quarks which then turn into pions and kaons.

For the calculation of the hadronization process we used the Lund Jetset 7.2 Monte Carlo simulation program [8]. This program, for any given initial configuration (i.e., the  $\chi - \chi$  annihilation final state  $F$ ), allows one to follow the hadronization and to infer the electron and  $\gamma$  final distributions. We have performed this analysis for each final state mentioned above. The statistical sample was taken to be  $2 \cdot 10^4$  events and the relevant physical parameters for each process were taken from the PDG [9]. It is worth mentioning that the photon and electron spectra computed at different center-of-mass energies  $E_{\text{cm}} \simeq 2m_\chi$ , when plotted in terms of the variable  $x = E/(E_{\text{cm}}/2)$ , exhibit remarkable scaling properties[10]. Thus  $\chi\chi$ -annihilation in the GC results in high energy ( $E_\gamma \gtrsim 100$  MeV) gamma-radiation, X-rays (mainly from the Compton scattering of the electrons), in gamma-ray lines (from  $\chi\chi \rightarrow \gamma\gamma$  and  $e^+e^- \rightarrow \gamma\gamma$  annihilation) and in radio-emission (from synchrotron radiation of electrons in magnetic fields). The estimates in ref.[2] show that expected high energy ( $E_\gamma \gtrsim 100$  MeV) gamma-radiation and radio-emission can be at the level of the observable fluxes or may exceed them.

The quantity of interest for observations is the integral gamma-ray flux

$$F_\gamma(>E_\gamma) = \frac{P}{4\pi r_\odot^2} \sum_F <\sigma v>_F \int_{x_\gamma}^\infty dx \left( \frac{dN_\gamma(x)}{dx} \right)_F \quad (8)$$

where  $P$  is given by (6),  $x = E_\gamma/m_\chi$ ,  $<\sigma v>_F$  is the  $\chi\chi$  annihilation cross section in the final state  $F$  and  $dN_\gamma(x)/dx$  is the photon energy spectrum mainly due to neutral pions decay. The existing limit [11] on gamma-ray flux from the GC is related to  $E_\gamma \sim 300$  MeV. More generally, for future experiments  $E_\gamma$  of interest is  $\sim 70 - 100$  MeV.

The energy flux for radio-emission at frequency  $\nu$  at Earth can be calculated as

$$F_\nu = \int_0^{m_\chi} dE_e Q_e(E_e) \int_0^{E_e} dE \frac{P(E, \nu)}{b(E)} \quad (9)$$

where  $E_e$  is the electron energy at generation,  $E$  is the electron energy at the moment of synchrotron radiation,  $b(E) = (dE/dt)_s$  is the synchrotron energy-loss of an electron and  $P(E, \nu)$  is the energy-loss of electron with energy  $E$  due to emission of photons with frequency  $\nu$ . The number of electrons with energy  $E_e$ ,  $Q(E_e)$ , generated per unit time in the GC due to  $\chi\chi$ -annihilation is given by

$$Q(E_e) = \frac{1}{m_\chi} P \sum_F \langle \sigma v \rangle_F \left( \frac{dN_e(x)}{dx} \right)_F \quad (10)$$

where  $x = E_e/m_\chi$  and  $dN_e(x)/dx$  is defined in the same way as  $dN_\gamma(x)/dx$ .

In the calculation of radio flux we assumed the magnetic field in the GC to be  $H = 10^{-2.5}$  G (see below).

We shall now briefly review the observational properties of the core of the GC following the references [12–13]. A violent activity is observed within a region of size  $\sim 1$  pc, which can be powered by  $\chi\chi$ –annihilation. The total bolometric luminosity, mostly due to the optical and UV radiation, is  $L_{\text{bol}} \simeq 4 \cdot 10^{40}$  erg s $^{-1}$ . The center of activity coincides with the compact non-thermal radio source Sgr A\*. It has an unusual rising spectrum  $F_\nu \simeq 1(\nu/10 \text{ GHz})^{1/4}$  Jy in the frequency range  $1 \text{ GHz} < \nu < 86 \text{ GHz}$ . Its luminosity is  $L_\nu = 1.3 \cdot 10^{34}$  erg s $^{-1}$  at wavelength  $\lambda > 3 \text{ mm}$ . The source is surrounded by a more extended radio halo.

The X–ray radiation ( $0.5 - 4.5$  KeV) from GC reveals [14] several compact sources one of which, with luminosity  $L_X \simeq 1.5 \cdot 10^{35}$  erg s $^{-1}$ , coincides with Sgr A\*. The extended X–ray component around this source has luminosity  $L_X \simeq 2.2 \cdot 10^{36}$  erg s $^{-1}$ .

High energy gamma–radiation from GC is not detected. The COS B upper limit at  $E_\gamma > 300$  MeV is  $F_\gamma < 4 \cdot 10^{-7}$  cm $^{-2}$  s $^{-1}$ . There are indications of the presence of a powerful flux ( $F_\gamma \sim 10^{-3}$  cm $^{-2}$  s $^{-1}$ ) in the form of 0.511 MeV e $^+e^-$ –annihilation line from GC. The core is submerged into a dust cloud, probably in the form of a ring with inner and outer radii of 2 pc and 4 pc, respectively. The dust absorbs a considerable part of the radiation from the core and reradiates it in the form of IR radiation. The phenomenological model of the core is developed in refs. [12,13]. It has been shown that the observations provide an overdetermined set of relations for the properties of the core; these are satisfied by a unique and plausible solution [12]. In particular, the mean magnetic field in the core is found to be  $\bar{H}_\perp = 10^{-2 \pm 0.5}$  G.

#### 4. Results and Conclusions

Let us turn now to the presentation and the discussion of our results. In Fig.1 we report the values of the neutralino relic abundance in the form of a scatter plot obtained by varying  $M_2$  and  $\mu$  in the ranges  $0 < M_2 < 6$  TeV and  $-3 \text{ TeV} < \mu < 3 \text{ TeV}$ , respectively. The other parameters are taken at the following values:  $\tan \beta = 8$ ,  $m_h = 50$  GeV,  $m_{\tilde{f}} = \tilde{m} = 3$  TeV ( $m_{\tilde{f}}$

denotes the mass of the sfermions, taken here to be degenerate). We notice that in this representative point of the parameter space many neutralino configurations provide large values for  $\Omega_\chi h^2$ ; for many configurations the relevant  $\Omega_\chi h^2$  value is even above the cosmological bound  $\Omega h^2 = 1$ . This situation occurs for gaugino-dominated compositions, since in this case  $\chi - \chi$  annihilation proceeds mainly through  $\tilde{f}$ -exchange, but this process is now strongly hindered due to the large value assigned to  $m_{\tilde{f}}$ .

In Fig.2 a scatter plot is displayed for the integral gamma-ray flux  $F_\gamma (> 300 \text{ MeV})$  evaluated from eq.(8). We remind that in the calculation of  $F_\gamma$  the rescaling for  $\rho_\chi^{\text{loc}} = \Omega_\chi \rho_{\text{DM}}^{\text{loc}}$  is used. Fig.2 shows that a large fraction of  $\chi$ -configurations with  $m_\chi \lesssim 100 \text{ GeV}$  are excluded by the COS B upper limit  $F_\gamma (> 300 \text{ MeV}) < 4 \cdot 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  [11]. For the configurations allowed by this limit, the graph does not show the values of  $\Omega_\chi h^2$ , i.e. it does not specify whether the neutralino can provide  $\Omega_{\text{CDM}} \sim 0.7$ . This information is added in Fig.3, where in a  $\mu - M_2$  diagram are displayed the  $\chi$ -compositions which satisfy the two following requirements: a)  $\Omega_\chi$  is within the range:  $0.5 \leq \Omega_\chi \leq 1$  which, taking  $h = 0.7$ , implies  $0.25 \leq \Omega_\chi h^2 \leq 0.5$ ; b) the relevant radio flux, as evaluated from eq.(9), does not exceed the experimental upper bound  $F_\nu < 1 \cdot 10^{-23} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}$  at  $\nu = 1 \text{ GHz}$  [12,13]. The neutralino configurations that meet these properties are denoted in Fig.3 by squares: they correspond to gaugino-dominated compositions with masses in the range  $100 \text{ GeV} \lesssim m_\chi \lesssim 500 \text{ GeV}$ . For these  $\chi$ -configurations the relevant gamma-ray flux is  $5 \cdot 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \lesssim F_\gamma \lesssim 2 \cdot 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ , i.e. this source is detectable with existing or future devices.

Fig. 4 displays the scatter plot of  $F_\gamma$  vs  $\Omega_\chi$  restricted to those configurations with mass  $20 \text{ GeV} \leq m_\chi \leq 100 \text{ GeV}$ , which satisfy the observational upper bound on radio-emission. The values  $\Omega_\chi < 0.1$  imply that CDM is composed mostly by some other particle(s), with neutralinos providing a small part of the CDM density. Fig. 4 shows that in this case the gamma-ray flux is marginally detectable down to  $\Omega_\chi \simeq 3 \cdot 10^{-4}$ . It means that the NGS model can be tested with the help of  $\chi\chi$ -annihilation even if the neutralino constitutes only a small part of CDM.

The general features of the previous discussion remain valid when we assign to the free mass parameters,  $m_{\tilde{f}}$   $m_h$ , values different from the previous ones. For instance we could assign to  $m_{\tilde{f}}$  the smallest possible value consistent with the LEP lower bound  $m_{\tilde{f}} > 45 \text{ GeV}$ [7] and with the condition that the neutralino in the lightest SuSy particle, and take for instance  $m_{\tilde{f}} = 1.2 m_\chi$ , when  $m_\chi > 45 \text{ GeV}$  and  $m_{\tilde{f}} = 45 \text{ GeV}$  otherwise.

In this case lighter sfermions make the  $\chi - \chi$  annihilation for gaugino configurations much more efficient than before. As a consequence, now the fluxes for gamma-radiation and for radio-emission, which are proportional to  $<\sigma v>_0 / (<\sigma v>_{\text{int}})^2$  are smaller than in the previous case (where sfermions were assumed to be very massive). However, our calculations indicate that a situation similar to that depicted in Fig.4 still persists, i.e. in a  $F_\gamma$  vs  $\Omega h^2$  plot many neutralino configurations densely populate a region where  $\Omega \sim 0.01 - 0.1$  with values of  $F_\gamma$  only very slightly below the experimental upper bound.

As a conclusion, we claim that the density distribution (1) of DM in our Galaxy results in a pointlike source of high-energy ( $E_\gamma > 100$  MeV) gamma-radiation with fluxes of order  $\sim 10^{-7} - 10^{-8}$  cm $^{-2}$  s $^{-1}$ , detectable with the help of present and futures techniques.

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### Figure Captions

**Figure 1:** Scatter plot of the neutralino relic abundance as a function of the neutralino mass. This scatter plot has been obtained by varying  $M_2$  and  $\mu$  in the ranges  $0 < M_2 < 6$  TeV and  $-3$  TeV  $< \mu < 3$  TeV respectively. The other parameters are taken at the following values:  $\tan \beta = 8$ ,  $m_h = 50$  GeV,  $m_{\tilde{f}} = \tilde{m} = 3$  TeV ( $m_{\tilde{f}}$  denotes the mass of the sfermions, taken here to be degenerate)

**Figure 2:** Scatter plot of the integral gamma-ray flux  $F_\gamma (> 300$  MeV) as a function of the neutralino mass. The ranges for  $M_2$  and  $\mu$  are the same as in Fig.1. Also the other parameters are taken at the same values as in Fig.1.

**Figure 3:**  $\mu - M_2$  diagram where the squares denote the  $\chi$ -compositions which satisfy the two following requirements: a)  $\Omega_\chi$  is within the range:  $0.5 \leq \Omega_\chi \leq 1$  which, taking  $h = 0.7$ , implies  $0.25 \leq \Omega_\chi h^2 \leq 0.5$ ; b) the relevant radio flux, as evaluated from eq.(9), does not exceed the experimental upper bound  $F_\nu < 1 \cdot 10^{-23}$  erg cm $^{-2}$  s $^{-1}$  Hz at  $\nu = 1$  GHz [12,13]. The gamma-ray flux for these configurations is  $5 \cdot 10^{-9}$  cm $^{-2}$  s $^{-1} \lesssim F_\gamma \lesssim 2 \cdot 10^{-7}$  cm $^{-2}$  s $^{-1}$

**Figure 4:** Fig. Scatter plot of  $F_\gamma$  vs  $\Omega_\chi$  restricted to those configurations with mass  $20$  GeV  $\leq m_\chi \leq 100$  GeV, which satisfy the observational upper bound on radio-emission.

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